August 4, 2021
Loma Linda Workshop

The open-source Treatment Planning Toolkit “matRad”

Introduction & Update on ongoing Developments and related Projects

Niklas Wahl

Group Radiotherapy Optimization
Department of Medical Physics in Radiation Oncology

DKFZ Heidelberg

Treatment Planning

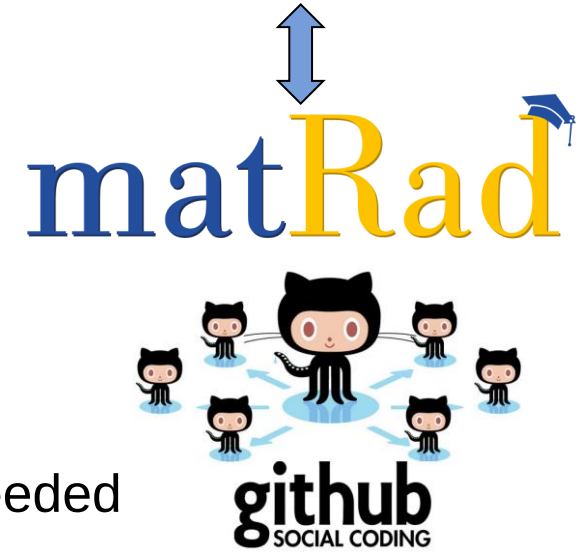
- computerized process
- dose is numerically simulated and optimized

Commercial solutions are closed systems (Black Box)	Research needs flexible, accessible software

Examples for research topics:

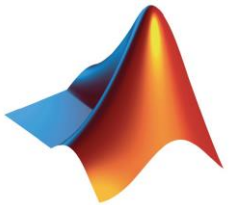
- Biological Optimization
  (RBE, effect, mixed-modality)
- Probabilistic dose calculation & optimization

→ low-level access to dose calculation / optimization needed



What is matRad?

- toolkit for three-dimensional intensity-modulated treatment planning for photons, protons and carbon ions
- Entirely written in Matlab & open source
- matRad implements well-established radiotherapy algorithms for research & education



Properties:

- **open-source code, patients and machine files on GitHub**
- **graphical user interface**
- **Non-linear constrained dose optimization (IPOPT)**
- **Import & export functionalities (DICOM, binary formats)**
- **No Matlab? → Octave compatibility & downloadable standalone**

Why? Supporting open science, reproducibility and education

www.matrad.org

Team

DKFZ Development team

Niklas Wahl
Lucas Burigo
Amit Ben Antony Bennan
Noa Homolka
Oliver Jäkel

HIT cooperation

Benjamin Ackermann
Swantje Ecker
Malte Ellerbrock
Andrea Mairani

Thomas Tessonnier
Katia Parodi (LMU Munich)

Advisors

Martin Siggel
Peter Ziegenhein

Alumni

Mark Bangert
Hans-Peter Wieser
Eduardo Cisternas
Ahmad Neishabouri
Cindy Herman
Thomas Klinge
Verena Böswald
Henning Mescher
Alexander Stadler
Guiseppe Pezzano
Lucas-Raphael Müller
Hubert Gabrys
Silke Ulrich
Oliver Schrenk
Paul Meder

Other Contributors

Eric Crhistiansen (Carleton University)
Steven van de Water (PSI)

BA 2279/3-1
WA 4707/1-1

H.-P. Wieser *et al.* (all authors above in **bold**), “Development of the open-source dose calculation and optimization toolkit matRad,” *Med Phys*, vol. 44, no. 6, pp. 2556–2568, 2017, doi: 10.1002/mp.12251.

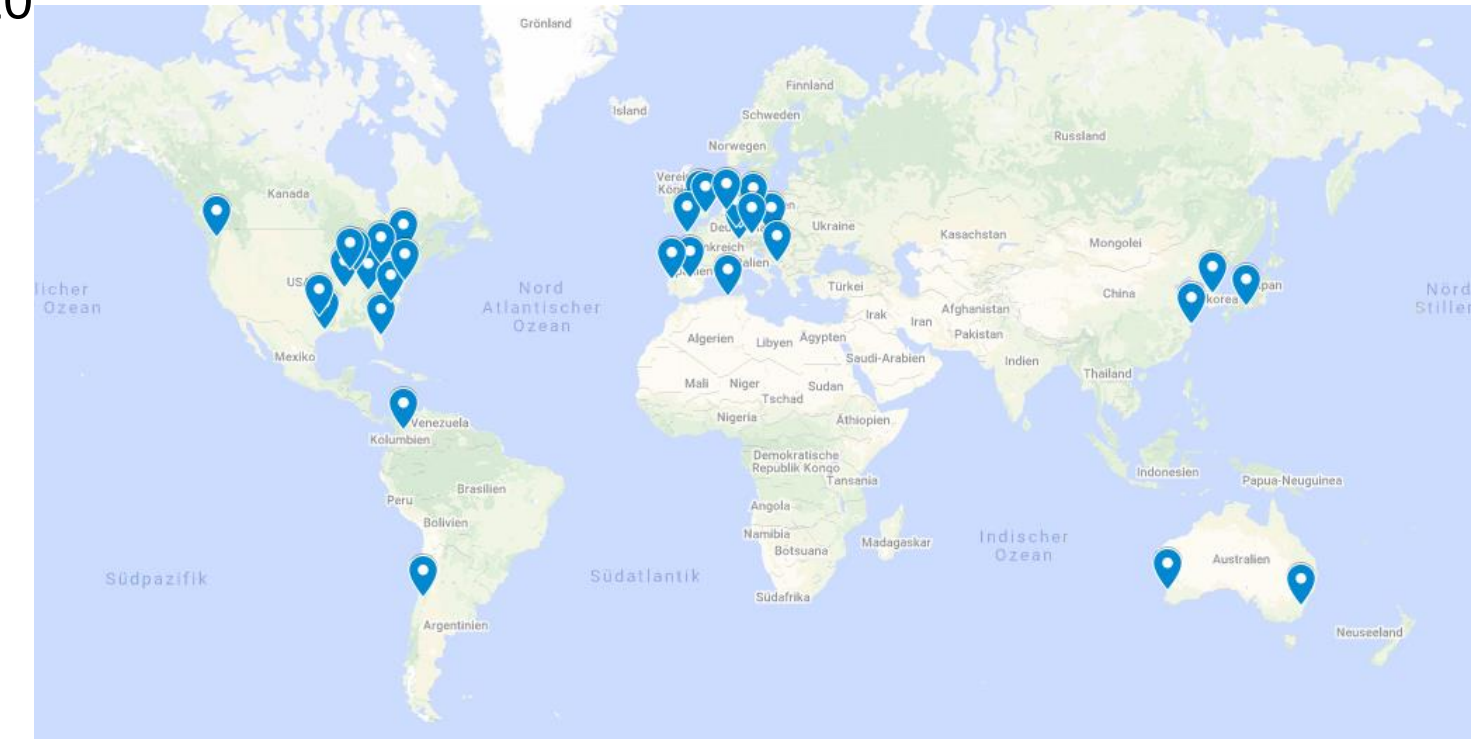
All Code Contributors: https://github.com/e0404/matRad/blob/master/AUTHORS.txt

More than 25 confirmed institutes somehow working with matRad

Start: 22. Januar 2015

1st commit 12cdfc1

- Github-Forks: >110



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Canada's Capital University

University of Zurich[UZH]

HIT Heidelberger Ionenstrahl-Therapiezentrum

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UNIVERSITY OF OXFORD

Technical University of Munich

University of Kentucky

THE UNIVERSITY OF WESTERN AUSTRALIA

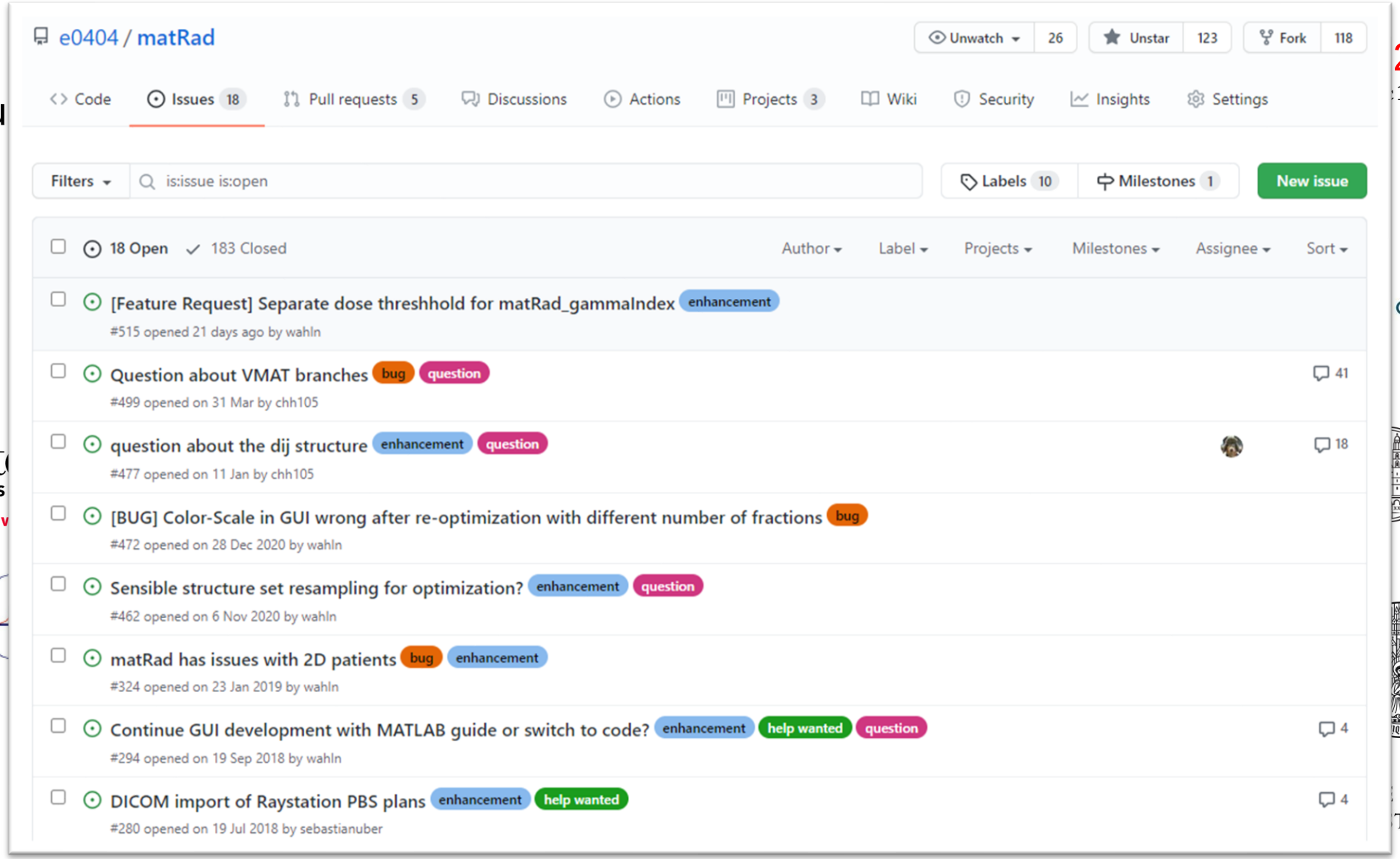
dkfz.

More than 25 confirmed institutes somehow working with matRad

- Githu

2015

:1



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TERN AUSTRALIA

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Current Release “Blaise” 2.10.1

- 3D dose calculation (validated)
  - Photons: SVD pencil-beam algorithm + sequencing
    MC interface to ompMC (open source)
  - Protons: Pencil-Beam algorithm + const. RBE
    MC interface to MCsquare (open source)
  - Carbon ions: Pencil-Beam algorithm + biol. effect / RBE
- Base data
  - Patient data (CORT data set) & DICOM Import
  - Physical (& biological) base data for photon LINAC as well as a proton and a carbon machine
- Inverse planning with new optimization interface
  - Photons: Physical dose optimization & DAO
  - Protons: + Constant RBE optimization
  - Carbon-ions: + RBE (1.1 or variable) or effect optimization
- Scripting & Graphical User Interface

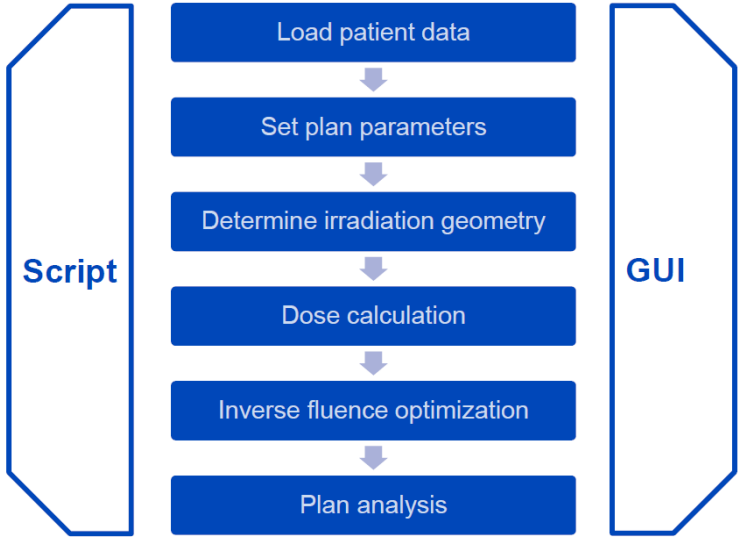
MEDICAL PHYSICS
The International Journal of Medical Physics Research and Practice

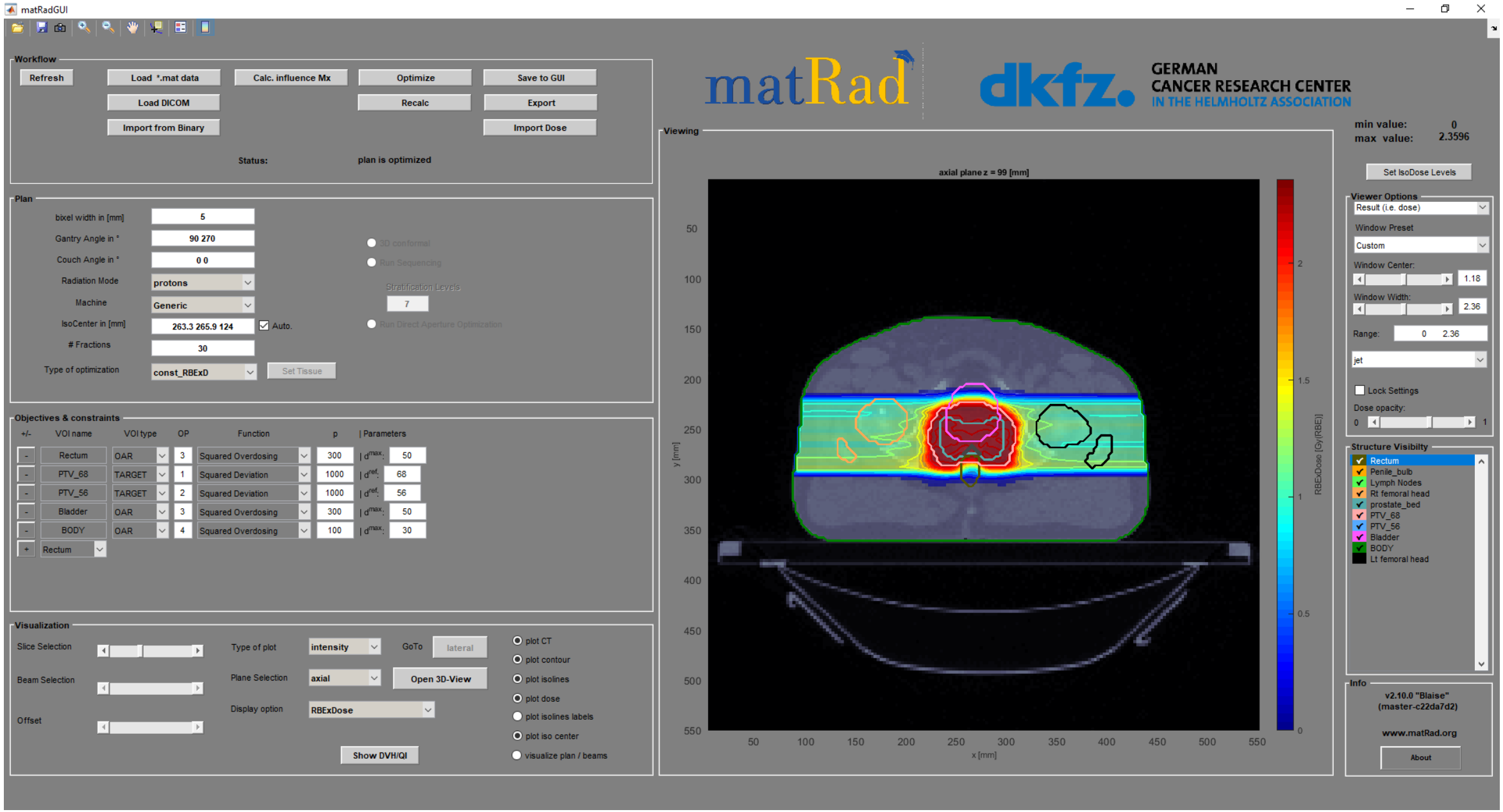
Research Article | Open Access

Development of the open-source dose calculation and optimization toolkit matRad

Hans-Peter Wieser, Eduardo Cisternas, Niklas Wahl, Silke Ulrich, Alexander Stadler, Henning Mescher, Lucas-Raphael Müller, Thomas Klinge, Hubert Gabrys, Lucas Burigo, Andrea Mairani, Swantje Ecker, Benjamin Ackermann, Malte Ellerbrock, Katia Parodi, Oliver Jäkel, Mark Bangert

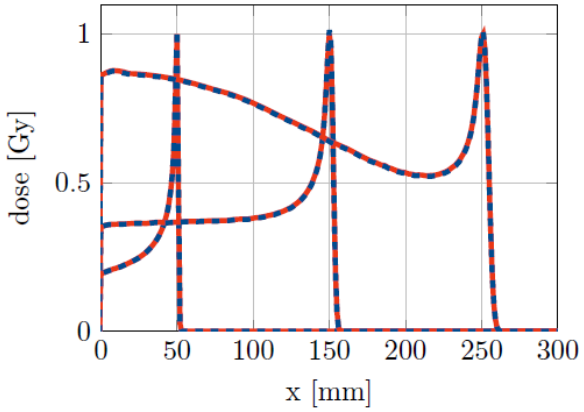
Wieser et al., 2017, Med Phys 44(6) among top 20 downloaded Med Phys papers in 2017

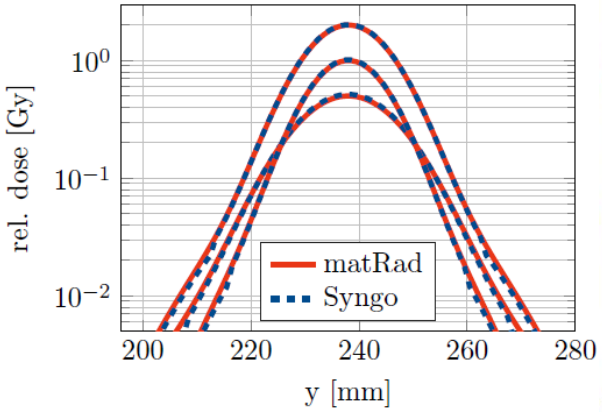


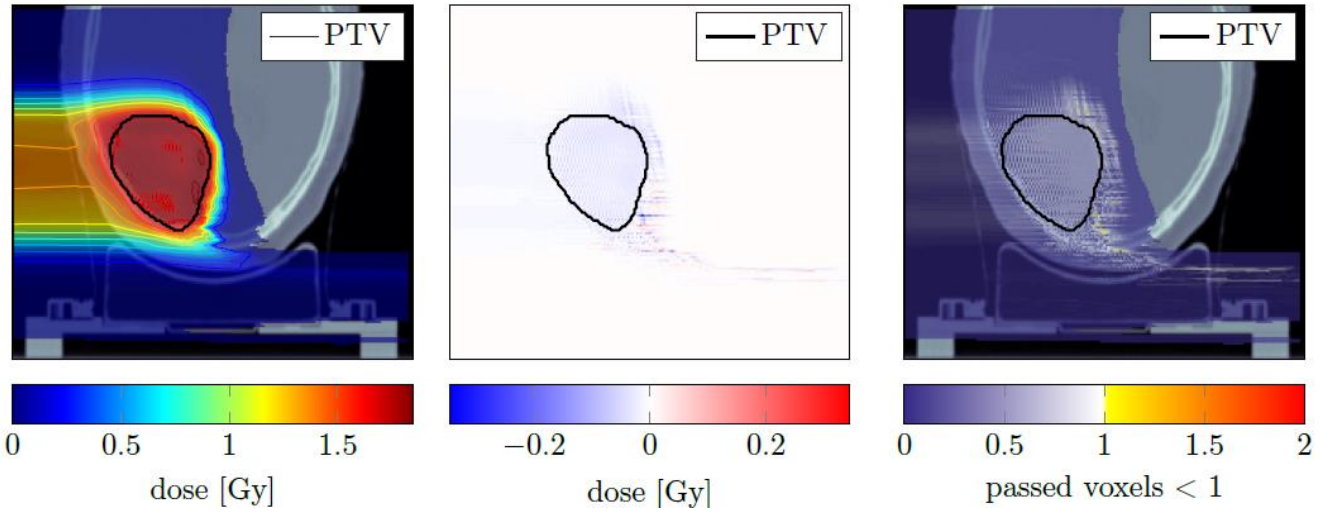

matRadGUI
Workflow
Refresh
Load *.mat data
Calc. influence Mx
Optimize
Save to GUI
Load DICOM
Recalc
Export
Import from Binary
Import Dose
Status:
plan is optimized
matRad
dkfz.
GERMAN CANCER RESEARCH CENTER
IN THE HELMHOLTZ ASSOCIATION
Plan
bixel width in [mm]
5
Gantry Angle in °
90 270
Couch Angle in °
0 0
Radiation Mode
protons
Machine
Generic
IsoCenter in [mm]
263.3 265.9 124
Auto.
Fractions
30
Type of optimization
const_RBExD
Set Tissue
3D conformal
Run Sequencing
Stratification Levels
7
Run Direct Aperture Optimization
Objectives & constraints
+/- VOI name VOI type OP Function p | Parameters
- Rectum OAR 3 Squared Overdosing 300 | d^max: 50
- PTV_68 TARGET 1 Squared Deviation 1000 | d^ref: 68
- PTV_56 TARGET 2 Squared Deviation 1000 | d^ref: 56
- Bladder OAR 3 Squared Overdosing 300 | d^max: 50
- BODY OAR 4 Squared Overdosing 100 | d^max: 30
+ Rectum
Visualization
Slice Selection
Beam Selection
Offset
Type of plot
intensity
GoTo
lateral
Plane Selection
axial
Open 3D-View
Display option
RBExDose
Show DVH/QI
plot CT
plot contour
plot isolines
plot dose
plot isolines labels
plot iso center
visualize plan / beams
Viewing
axial plane z = 99 [mm]
y [mm]
x [mm]
RBExDose [Gy(RBE)]
min value: 0
max value: 2.3596
Set IsoDose Levels
Viewer Options
Result (i.e. dose)
Window Preset
Custom
Window Center: 1.18
Window Width: 2.36
Range: 0 2.36
jet
Lock Settings
Dose opacity: 0 1
Structure Visibilty
Rectum
Penile_bulb
Lymph Nodes
Rt femoral head
prostate_bed
PTV_68
PTV_56
Bladder
BODY
Lt femoral head
Info
v2.10.0 "Blaise"
(master-c22da7d2)
www.matRad.org
About

Validation against Syngo Siemens - γ-index > 99.67% (2%,2%)

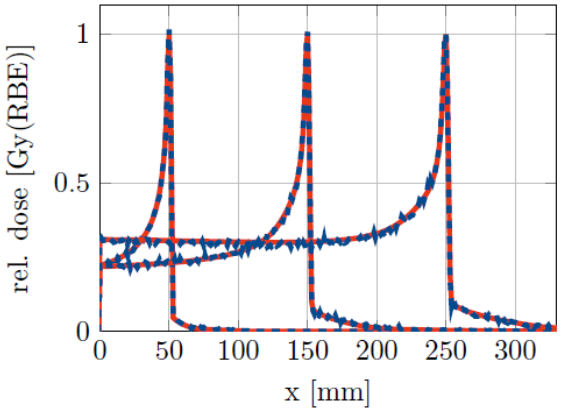
Protons:



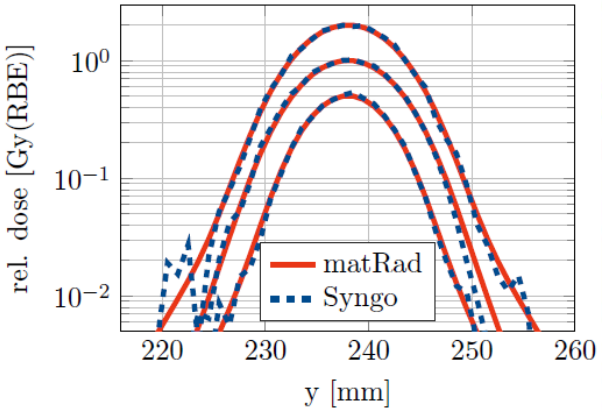




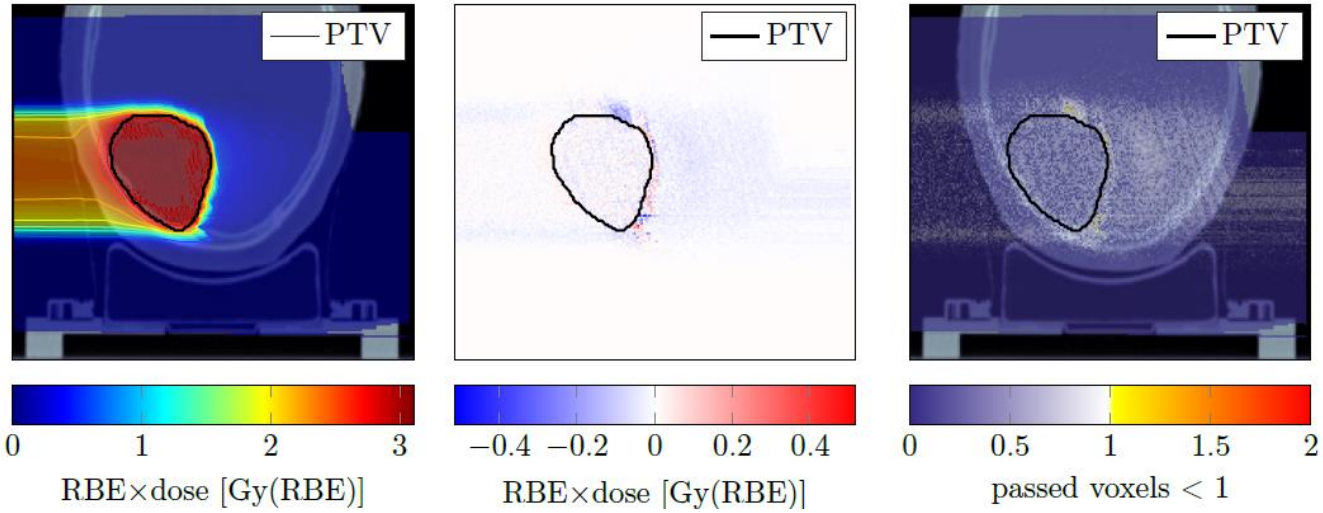
Carbon Ions:



(a) central depth dose profiles



(b) lateral dose profiles



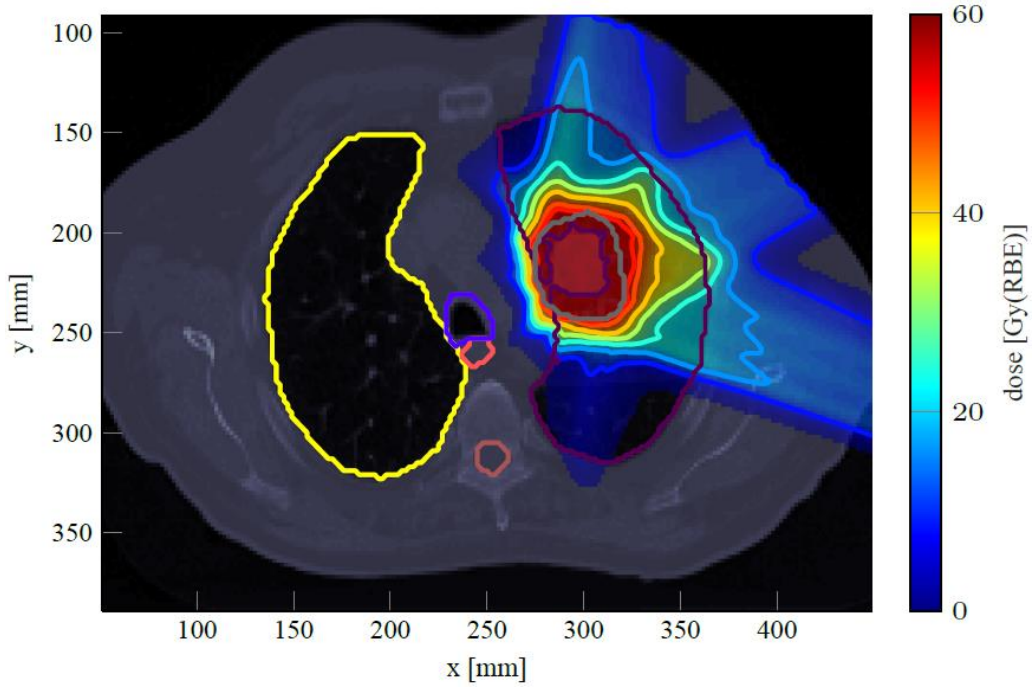
Performance of matRad - Intel Core i7 2.8 GHz, 32 GB RAM

modality -	setting	#beams	#bixel	D_{ij} elem. [1e6]	D_{ij} size [GB]	t_{dose} [s]	#iter.	t_{opt} [s]
photons	82 mm D_{ij} samp.	4	2608	172	2.75	295	145	82
photons	40 mm no samp.	4	2608	99	1.59	101	143	44
photons	82 mm D_{ij} samp.	8	3877	426	6.81	741	51	140
photons	40 mm no samp.	8	3877	236	3.77	226	51	66
photons	40 mm D_{ij} samp.	72	13597	567	9.07	853	147	407
protons	99.75 % SG	1	7797	19	0.29	22	123	41
protons	99.75 % DG	1	5955	87	1.38	46	171	109
protons	99.75 % SG	3	28097	56	0.89	68	67	187
protons	99.75 % DG	3	24137	269	4.30	160	262	330
protons	99.75 % SG	2	45574	116	1.86	97	218	137
protons	99.75 % DG	2	27683	520	8.33	299	197	486
carbon	99.75 % SG	1	11780	160	2.55	67	72	92
carbon	99.75 % DG	1	9963	537	8.61	203	79	225
carbon	99.75 % SG	3	42810	411	6.68	310	117	193
carbon	99.75 % DG	3	31205	756	12.1	560	107	365
carbon	99.75 % SG	2	24612	336	5.88	137	177	273
carbon	99.50 % DG	2	16889	855	17.94	472	134	521

Throughput Optimization: 6 GB/s

Development & Research Branches → Hopefully in the next release

- Helium base data (physical & biological)
  `-dev_varRBErobOpt`
- Robust / probabilistic optimization & uncertainty quantification
  `-dev_varRBErobOpt`
- Variable RBE & effect for protons
  `-dev_varRBErobOpt`
- New GUI (Object-oriented & modular, Octave compatible)
  `-dev_classGUI`
- Extended MC interfaces (presented last year by Lucas)
  `-dev_MonteCarlo`
- External contributions:
  - VMAT `-dev_VMAT(Eric Christiansen)`
  - optimization `-dev_exactOpt (Steven van de Water)`



Proton plan with MCsquare
2e4 histories/beamlet, 4689 beamlets
120 min at $(2.5mm)^3$ resolution

Evaluated on Desktop PC, i7-6700 @ 3.4 GHz (4 cores +HT)

Current Developments at DKFZ

Software Development:

- Unit Testing Framework for Core Functionality
- Python Interface
- Refactoring code for modularization

Future:

- Research Software Engineer position funded by DFG (3 years, WA 4707/1-1)
  - Further professionalization (CI)
  - Helpdesk & Community building
  - ML / AI functionality
  - Interfaces to other open-source software

Research-oriented:

- NTCP models & optimization
- Carbon Monte Carlo & Lung degradation
- Joint / mixed-modality / spatio-temporal optimization
  → Presentation by Amit
- Proton FLASH Planning Tools
- Efficient many-scenario probabilistic planning based on variance objectives
- Superiorization for Inverse Planning
  → Presentation by Florian

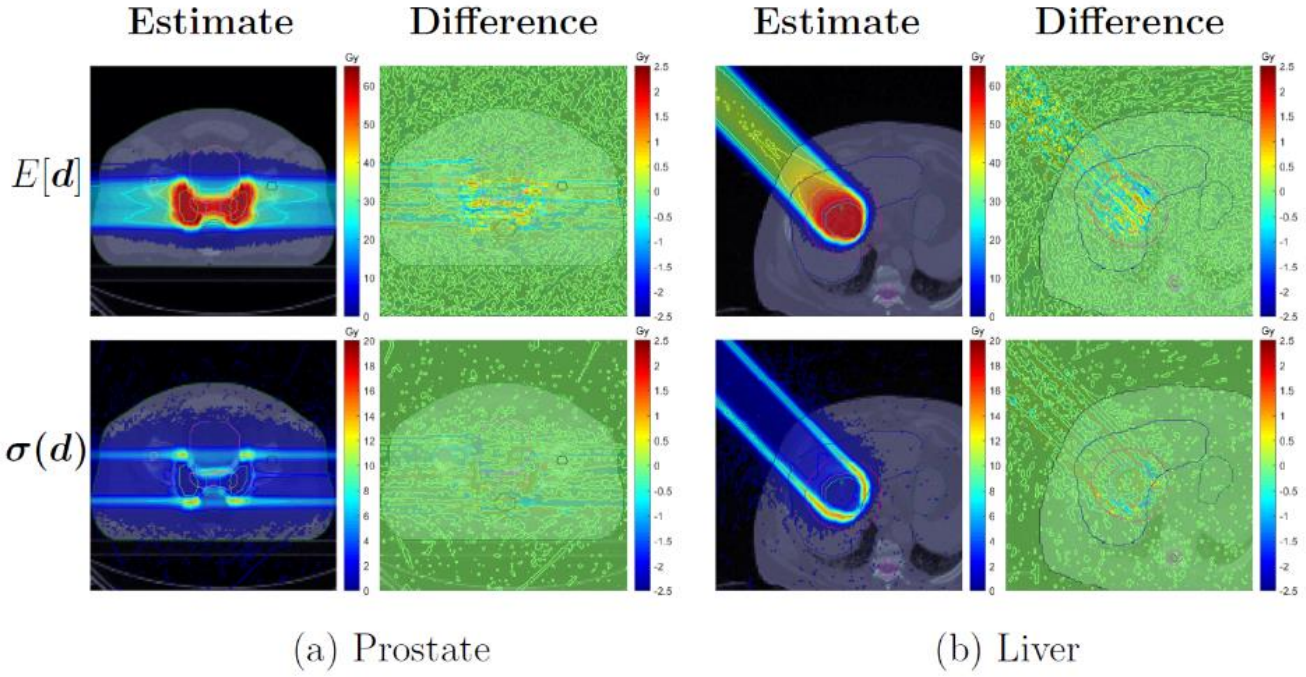
Example matRad Projects

Example Project: MC Dose Uncertainty Quantification (P. Stammer, KIT / DKFZ)

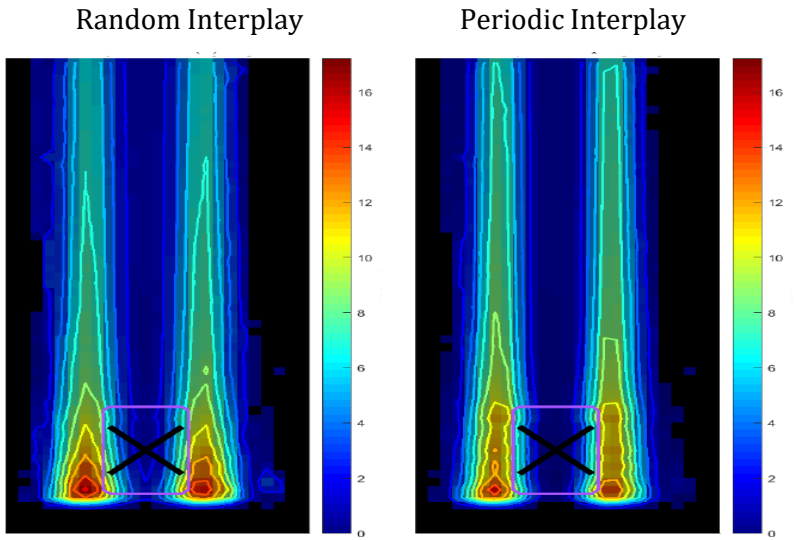
- Avoid computation of explicit error / sample scenarios for robustness analysis and robust optimization with Monte Carlo codes

  → Re-weighting of histories of a single simulation for uncertainty estimation

- Input Uncertainty modeling of static & time-dependent beam application/movement patterns using pencil beam correlations



Estimates of expected dose and variance using the reweighting approach and their difference to a reference [1]



Dose standard deviation in a waterbox for random vs. periodic movement pattern / interplay during treatment

Other Involvments at KIT:

- Development of KiT-RT: A Kinetic Transport Solver for Radiation Therapy (https://github.com/CSMMLab/KiT-RT)
- (Dynamical) low rank methods for more time and space efficient UQ in radiative transport

[1] Stammer, P., Burigo, L., Jäkel, O., Frank, M., & Wahl, N. (2021). Efficient uncertainty quantification for Monte Carlo dose calculations using importance (re-) weighting. https://arxiv.org/abs/2106.11885

Example Project – Biological dose degradation in lung tissue (N. Homolka)

- Sub-voxel microstructures degradation in Lung in general not captured in deterministic and MC dose calculation

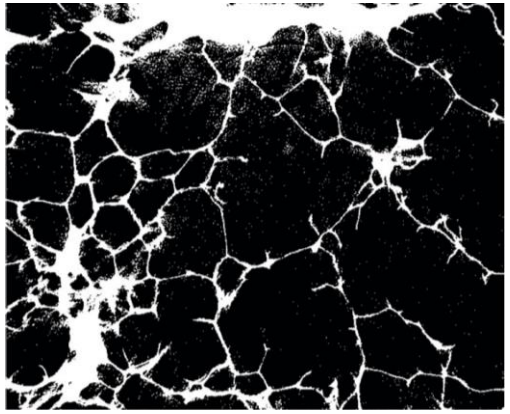


Figure 1: µCT image of a human lung (binarized) [Baumann et al., 2017].

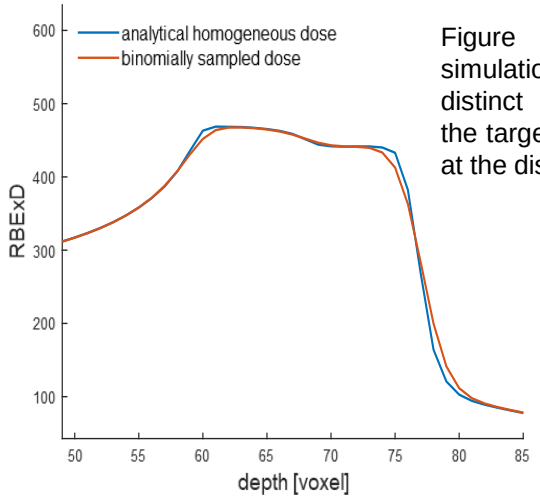


Figure 2: Pencil beam simulations showing the distinct underdosage of the target and overdosage at the distal edge.

- Can be approximated with voxel density & material sampling techniques or analytical convolution techniques

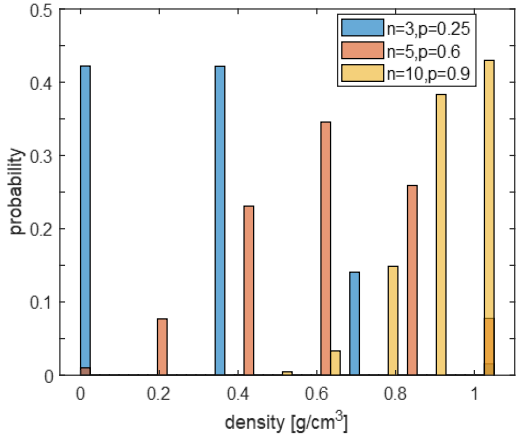


Figure 3: Normalized histogram for 3 different cases for „number of structures in 1 voxel“ and „density of that voxel“

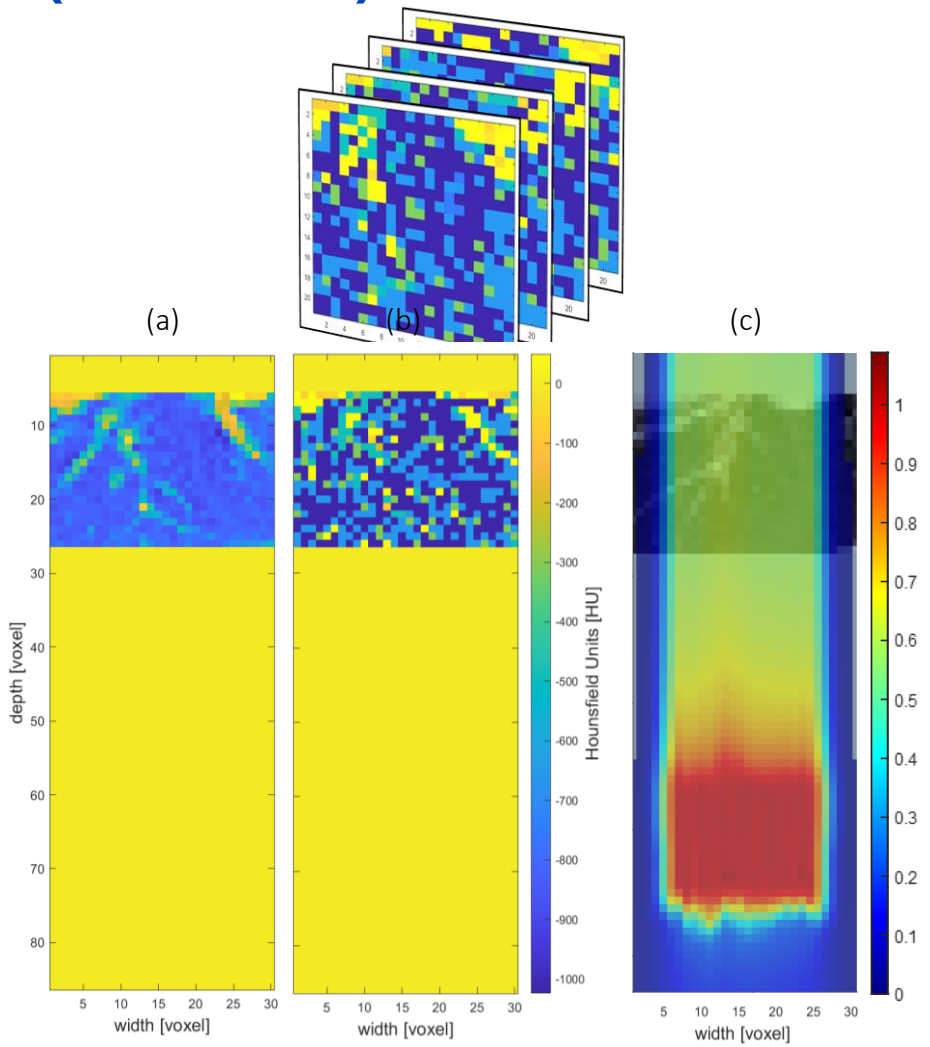


Figure 2: Waterphantom with slab of lung copied from real patient (a), phantom with binomially sampled lung (b), and calculated dose slice averaged over 100 samples (c).

Example Education & Outreach: Particle Therapy Master Class

- Shall become part of the “International Masterclasses – Hands on Particle Physics” (https://physicsmasterclasses.org/)
- Educational course for school children
- Introduced by DKFZ/GSI/CERN (Main coordination: Yiota Foka, at DKFZ: Niklas & Joao)

  → First successful stresstests in April 2019 & 2021

Conclusion

- matRad is an open-source treatment planning toolkit with focus on **research** & **education**
- Used within **internal & external** research projects / collaborations
- **Dose calculation** & **treatment planning** for photons, protons, helium and carbon (including base data & data import)
- **Active, often research-oriented, development** (internal & external)
  - Monte Carlo interfaces
  - new modalities / optimization techniques
- Efforts in **professionalizing** software development (i. e., continuous integration)

How to get going with matRad?

1. Go to our page on GitHub: **www.matRad.org**

2. Download the Code, or even better: Familiarize with **git** and Clone

3. Checkout the UI & the code
   - `matRadGUI.m` & `matRad.m`
   - many examples in the `examples/` folder
   - Wiki on GitHub: **https://github.com/e0404/matRad/wiki**

4. Ask us from E040-4 for help

5. Profit (and contribute)!

MATLAB

GNU Octave

GPL v3 Free Software
Free as in Freedom

GitHub

www.matrad.org

matRad

Data IO

- DICOM
- *.nrrd, *.mha, *.vtk
- CERR
- VOXELPLAN

Dose calculation

- Photons
  - SVD pencil beam
  - ompMC interface
- Particles
  - IMPT pencil beam
  - MCSquare interface
  - TOPAS interface
  - Analytical probabilistic modeling

Analysis & visualization

- GUI CT & dose distribution browser
- Dose statistics
- DVHs

Dose optimization

- Fluence and experimental direct aperture optimization
- IPOPT https://projects.coin-or.org/Ipopt
- Matlab's proprietary fmincon
- Superiorization
- Objectives: Quad. dose deviation, mean dose, EUD, DVH
- Constraints: Min, max, mean dose, EUD, DVH
- Xia, Engel, Siochi MLC sequencer
- Robust and stochastic optimization
- Variable RBE optimization for protons
- Coverage based optimization
- Analytical probabilistic modeling
- VMAT

Base data

- Patient data (CT & RTSS)
- Photon pencil beam base data
  → https://github.com/e0404/photonPencilBeamKernelCalc
- Generic proton and carbon ion pencil beam base data
- Carbon ion biological base data (LEM IV)
- Helium pencil beam base data
- Helium biological model

Thank you for your attention!

Features in blue are available on development branches

dkfz.